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SUMMARY

This report discusses the design of forebody shapes for natural laminar flow. For subsonic flow, computed results for three shapes of different fineness ratios indicate that laminar flow can be attained under conditions that approximate those on the forebody of a cruise missile flying at a low altitude at a high subsonic Mach number. For supersonic (Mach 2.00) design, a one-parameter family of hyperbolic arcs was used to generate forebody shapes having a favorable pressure gradient over the forebody length. Computed results for these shapes indicated laminar and transitional flow over the range of Reynolds numbers considered.

INTRODUCTION

A recurring proposal for reducing the drag of an aerodynamic configuration is to increase the extent of the laminar boundary-layer flow over the configuration. Work currently in progress has concerned both natural laminar flow and laminar flow control (LFC) airfoils.

Laminar flow design has also been applied to axisymmetric shapes such as the forebodies of torpedoes, missiles, and some airplanes. Reference 1 presents an example of a "dolphin" torpedo shape obtained by revolving the coordinates of an NACA laminar flow airfoil about the axis. Within a limited Reynolds number range, it is possible, as in this example, to design for laminar flow beyond the point of maximum thickness. However, since the design aft of the forebody is often dictated by other factors (payload construction considerations, etc.), the application of laminar design is generally limited to the forebody.

Recent studies include an experimental investigation at low speeds of transition on nine axisymmetric forebody shapes (ref. 2). These shapes were determined by a systematic variation of geometric parameters, not by a requirement for an extensive laminar flow region.

Forebody shapes designed specifically for a long laminar run at compressible free-stream velocities have apparently not been extensively studied. This paper presents some analytical-computational results of an investigation of such forebodies. Experimental studies of these forebody shapes were not conducted, primarily because of the difficulty of accounting for the influence of tunnel noise and free-stream turbulence on transition in wind-tunnel tests. Important research on this problem has been reported (ref. 3), but the question of the effect of the frequency of the disturbances has yet to be resolved (ref. 4).

Situations that correspond to small Reynolds number flows, such as small configurations (most remotely piloted vehicles) or flight at low speeds or altitudes represent rather obvious potential applications of laminar flow design. For the present study, however, free-stream Reynolds numbers that correspond to more difficult, borderline situations, such as a low-altitude cruise

missile and a supersonic aircraft traveling at a moderately high altitude are assumed. The results, of course, are not limited to a specific application or configuration.

SYMBOLS

Measurements are given in SI units. Calculations were made in U.S. Customary Units.

a,b,k	parameters in equation of hyperbola (eq. (1)), m
$C_{D,f}$	friction drag coefficient referenced to maximum cross-section area
C_p	pressure coefficient
l	forebody length, m
M	free-stream Mach number
R_∞	free-stream Reynolds number
r	radial coordinate, m
r_f	forebody radius at shoulder, m
x	axial coordinate, m
Γ	transition intermittency factor

Subscript:

T	beginning of transition

ANALYTICAL AND COMPUTATIONAL METHODS

Subsonic Forebody Shapes

Each of the forebody shapes was designed to have a favorable pressure gradient (expansion) over the entire forebody. For subsonic shapes, the design method was to assume an initial shape, compute its pressure distribution, and then alter the shape to approximate better the desired pressure distribution (one that represents the most favorable gradient within the geometric constraints). This tailoring was accomplished by altering the relative local streamwise curvature in proportion to the desired local relative velocity increment, in a manner somewhat similar to the two-dimensional method of reference 5.

The inviscid pressure distributions were computed by the method of reference 6. This method represents a numerical solution of the inviscid potential flow equations for a subsonic free-stream Mach number. In any such numerical

technique the interpolation routines often give rise to spuriously high curvatures. In order to minimize this effect, low-order polynomial interpolation was used, and input locations were matched very closely with calculation points.

The boundary-layer calculations were made by the method of reference 7. This method computes laminar, transitional, and turbulent boundary layers. The point at which transition begins is determined as the location at which the computed local vorticity (disturbance) Reynolds number reaches an empirically determined critical value. This critical value was taken to be 2896, in accordance with the results of reference 3. It was determined by measuring the transition location on a cone under a variety of tunnel flow conditions, and then extrapolating the results to determine the value that would be obtained at a free-stream disturbance level of zero.

Supersonic Forebody Shapes

The supersonic forebodies were also designed to have a favorable pressure gradient over the entire forebody length. A single shape was initially designed by the method of reference 8. It was necessary to approximate this shape with an analytic expression because the design was checked by an early specialized version of the STEIN code (ref. 9) which requires input geometry in analytic form. A hyperbolic arc was found to be an appropriate curve for approximating the original design. Subsequently, other shapes were generated by varying a specific parameter in the hyperbola formula. Of course, it is possible that an analytic expression exists that is even more effective for this purpose than the hyperbola formula.

The STEIN code represents a numerical solution of the exact inviscid equations for supersonic flow. The method of reference 7, with appropriate allowances for the supersonic situation, was used for the boundary-layer calculations.

RESULTS AND DISCUSSION

Subsonic Forebody Shapes

Three blunt subsonic forebody shapes, designed according to the principles described in the previous section, are shown in figure 1. The coordinates are given in table I.

The nominal design parameters were $R_{\infty} = 1.36 \times 10^8$ per meter and $M = 0.75$. These conditions apply approximately to a low-flying cruise missile with a 0.51-m diameter. This example was chosen, in spite of the practical problems associated with maintaining laminar flow at low altitudes, because it represents a fairly extreme situation. The designs would perform better in any context that involved a lower free-stream Reynolds number.

The inviscid pressure distributions are shown in figure 2 for $M = 0.75$. Similar calculations were performed for $M = 0.70$ and $M = 0.80$. When compressibility effects are significant (at high subsonic Mach numbers), an

increase in M causes a slight increase in the pressure gradient up to the shoulder. For the 2:1-fineness-ratio body, the computed pressure coefficient at the shoulder suction peak changes from -0.226 to -0.262 as the Mach number is increased from 0.70 to 0.80. For the lower fineness ratio bodies, the increase is somewhat greater.

The compressibility effect, although small for bodies of revolution, tends to offset partially the increase in R_∞ that accompanies an increase in M and thereby the sensitivity of the laminar flow performance to Mach number variation. Thus, the design performance is significantly less sensitive at subsonic speeds to an increase in M than it is to an increase in R_∞ resulting from an increase in vehicle size or free-stream pressure.

This fact is demonstrated by the results for the 2:1-fineness-ratio body which are summarized in the following table, where Γ, the transition intermittency factor, varies from 0.0 to 1.0 as the flow progresses from fully laminar to fully turbulent in the transition region.

Case	M	R_∞/m	x_T/l	Γ at $x = l$	$C_{D,f}$
1	0.70	1.27×10^8	0.61	0.38	0.00315
2	.75	1.36	.56	.68	.00436
3	.80	1.45	.54	.69	.00423
4	.75	1.51	.49	.91	.00590

The friction drag $C_{D,f} = 0.00436$ (case 2) compares with a value of 0.01473 which is calculated for a fully turbulent boundary layer.

Although a fineness ratio of 2:1 does not represent the upper limit for laminar flow design at such high Reynolds numbers, the design problems become formidable if a more slender design is attempted. The most direct problem is that the longer meridian arc length gives rise to larger values of local Reynolds number. Furthermore, the pressure gradient becomes more gradual as the body is lengthened. Finally, the nose radius must become smaller in order to obtain the required favorable pressure gradient. This problem is of special concern for those applications that require a large electronics package in the nose region. On the other hand, the potential gain in terms of drag reduction is greater for a longer forebody.

The 1:1-fineness-ratio body, in contrast to the forebody with a 2:1 ratio, has a much stronger favorable pressure gradient over its entire length. Calculations for the design case indicate that the boundary layer is laminar to the shoulder. No other calculations were performed for this forebody because such a short forebody is of relatively little interest from the standpoint of friction drag minimization.

The intermediate shape, with a fineness ratio of 1.5:1 is the most interesting case. For this fineness ratio, the boundary layer is fully laminar over the forebody both at the design conditions and when M is increased

to 0.80 with the correspondent increase in R_∞. The effect of the steepening pressure gradient (see fig. 2(b)) is to cause the vorticity Reynolds number to remain nearly constant over the aft 30 percent of the forebody. Computed results for this forebody are summarized in the following table:

M	R_∞/m	x_T/l	Γ at $x = l$	$C_{D,f}$
0.70	1.27×10^8	1	----	0.00253
.75	1.36	1	----	.00256
.80	1.45	1	----	.00256
.75	1.51	.80	0.30	.00283

Supersonic Forebody Shapes

Although the design problem for the supersonic speeds is usually dominated by wave drag considerations, there is, nevertheless, some advantage to be realized by reducing the skin friction losses.

As was mentioned in the Introduction, the supersonic forebody shapes were required to have a favorable pressure gradient over their entire length and to be mathematically representable with an analytic expression. A hyperbolic arc was found to satisfy these requirements. If one specifies that the body slope be zero at $x = l$, the equation of the hyperbola is

$$\frac{r - k}{b} = -\sqrt{1 + \left(\frac{x - l}{a}\right)^2} \tag{1}$$

The condition that the body radius be r_f at $x = l$ yields the relation

$$r_f = k - b \tag{2}$$

Requiring the hyperbola to pass through the origin gives the result

$$\frac{k}{b} = \sqrt{1 + \left(\frac{l}{a}\right)^2}$$

or

$$\frac{a}{l} = \frac{1}{\sqrt{\left(\frac{k}{b}\right)^2 - 1}} \tag{3}$$

Therefore, if k is specified arbitrarily, then b is determined by equation (2) and a by equation (3). Thus, there is a one-parameter family of hyperbolas that satisfies the geometric conditions.

The shape and its corresponding pressure distribution become relatively insensitive to variations in the parameter k as it increases. This fact is demonstrated by the results shown in figure 3. For a forebody fineness ratio of 2.5:1 ($r_f = 1$, $l = 5$), calculations were performed for k values of 2, 5, and 11. For this range of k values the nose semiangle varies from 16.6° to 20.8°.

The two extreme cases, $k = 2$ and $k = 11$, were then scaled to a diameter of 0.9144 m at the shoulder, and boundary-layer calculations were performed for stream conditions $M = 2.00$ and $R_\infty = 8.23 \times 10^7$ per meter. These conditions correspond roughly to those on the forebody of a small fighter flying at an altitude of 16 760 m.

The smaller value of k corresponds to the shape with the smaller nose angle and consequently, lower wave drag. The larger value of k, on the other hand, yields a forebody with slightly more volume. The calculated boundary-layer characteristics for the two bodies are very similar, as indicated by the following table:

k	R_∞/m	x_T/l	Γ at $x = l$	$C_{D,f}$
2	8.23×10^7	0.760	0.440	0.00393
11	8.23	.766	.325	.00382
2	9.15	.674	.767	.00510
11	9.15	.684	.695	.00483
2	10.45	.581	.944	.00658
11	10.45	.582	.924	.00636

The friction drag coefficient, $C_{D,f} = 0.00382$, for $k = 11$ and $R_\infty = 8.23 \times 10^7$ per meter compares with a value of 0.01607 calculated for a fully turbulent boundary layer.

Boundary-layer characteristics are more sensitive to Mach number variation at supersonic speeds because an increase in Mach number is accompanied by a decrease in the pressure gradient. This effect is illustrated in figure 3(a), which compares the pressure distributions at $M = 2.00$ and $M = 2.50$ for the $k = 2$ forebody.

If a body of revolution is set at an angle of attack, the cross flow over the circular cross section has a favorable pressure gradient over the lower surface and an unfavorable gradient over the upper surface. Consequently, setting the body at a small angle of attack would tend to delay the beginning of transition on the lower surface and advance it on the upper surface. Similar considerations hold for small yaw angles.

CONCLUDING REMARKS

Analytical-computational results for several body shapes designed for long runs of natural laminar flow have been presented. Studies of three subsonic forebody designs indicate that laminar flow can be attained under conditions that approximate those on the forebody of a cruise missile flying at a low altitude at a high subsonic Mach number. Each design represents a compromise with geometric constraints and so is not optimal with regard to length of laminar run.

For supersonic (Mach 2.00) design, a one-parameter family of hyperbolic arcs was used to generate forebody shapes having a favorable pressure gradient over the forebody length. Computed results for these shapes indicated laminar and transitional flow over the range of Reynolds numbers considered. Since the boundary-layer characteristics are relatively insensitive to variations in this hyperbolic arc parameter, the shapes having a smaller nose angle are preferable from the standpoint of wave drag consideration, but with some penalty in volume.

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December 8, 1978

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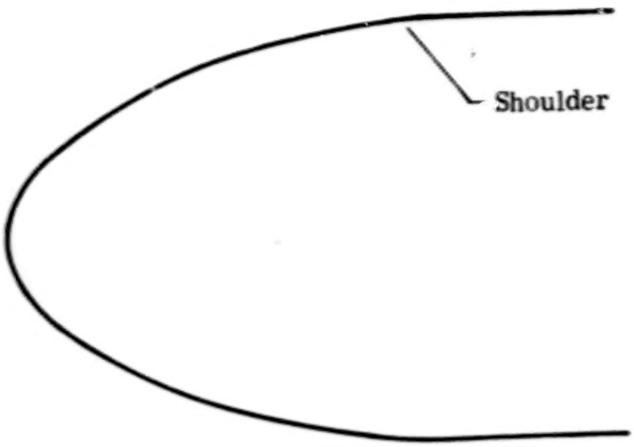
TABLE I.- COORDINATES FOR FOREBODIES HAVING FAVORABLE PRESSURE GRADIENT

OVER ENTIRE FOREBODY LENGTH AT $M = 0.75$

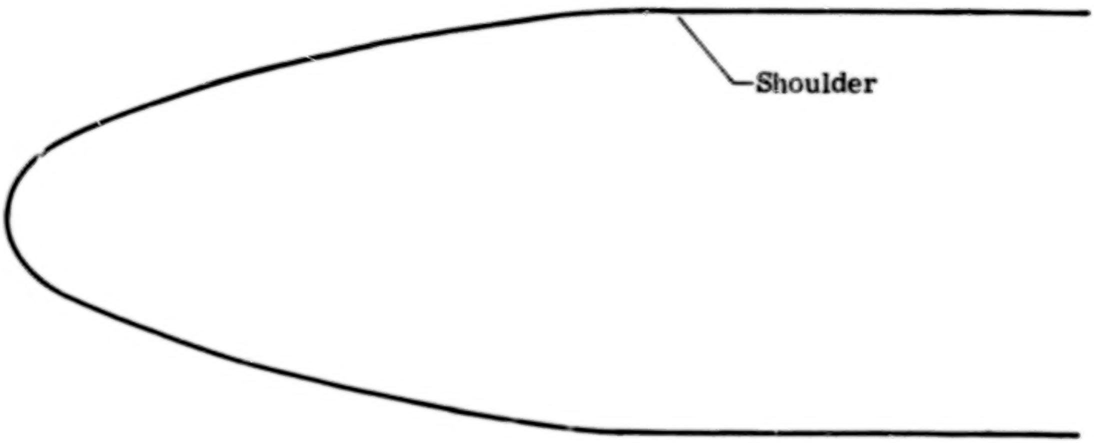
x/r_f	r/r_f
1:1-fineness-ratio body	
0.00	0.00
.0049	.0500
.0208	.1200
.5375	.2010
.1246	.3090
.2394	.4220
.6101	.6520
.8475	.7560
1.0980	.8380
1.3470	.9050
1.5670	.9480
1.7460	.9760
1.8730	.9912
1.95	.9972
2.00	1.00
1.5:1-fineness-ratio body	
0.00	0.00
.01	.10
.05	.18
.11	.253
.19	.325
.29	.380
.43	.447
.60	.511
.79	.578
1.00	.6395
1.23	.703
1.46	.759
1.70	.812
1.93	.858
2.15	.898
2.36	.932
2.54	.957
2.70	.9755
2.82	.9876
2.92	.995
2.98	.999
3.00	1.00

TABLE I.- Concluded

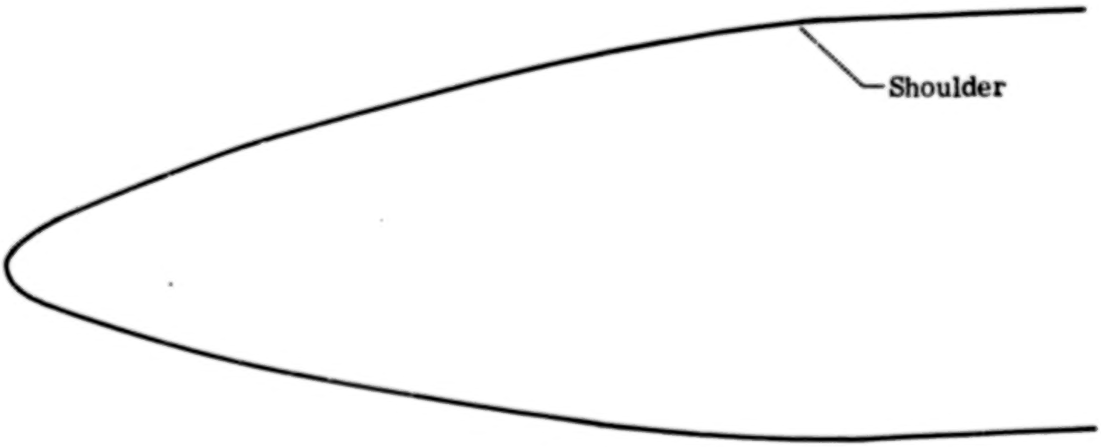
x/r_f	r/r_f
2:1-fineness-ratio body	
0.00	0.00
.01	.05
.03	.08
.07	.121
.13	.161
.23	.212
.36	.263
.52	.325
.71	.285
.93	.454
1.19	.524
1.47	.598
1.78	.669
2.10	.739
2.44	.8045
2.78	.864
3.11	.9125
3.43	.954
3.72	.981
3.99	.999
4.00	1.00



(a) Fineness ratio = 1:1.



(b) Fineness ratio = 1.5:1.



(c) Fineness ratio = 2:1.

Figure 1.- Subsonic forebody designs of various fineness ratios.

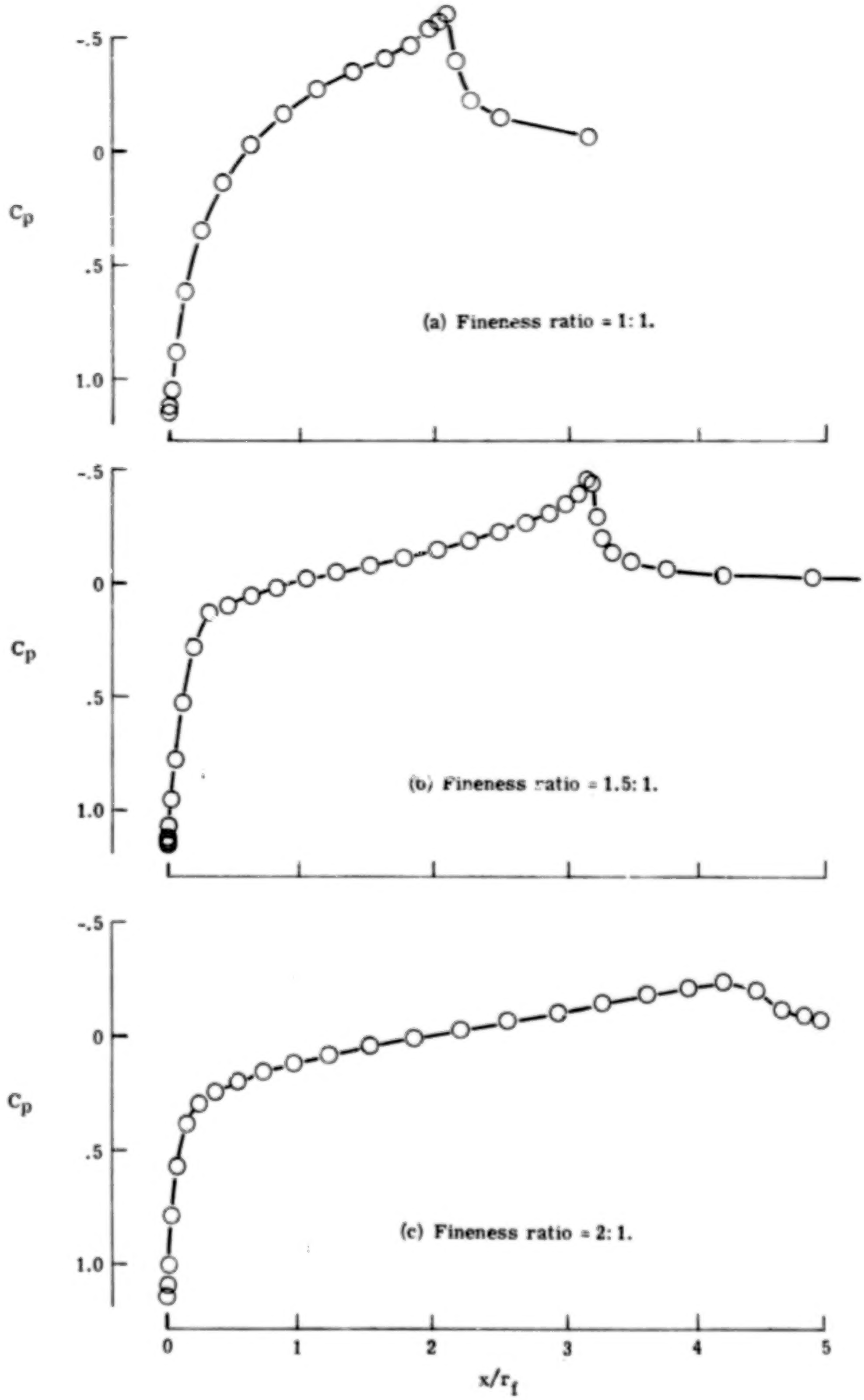
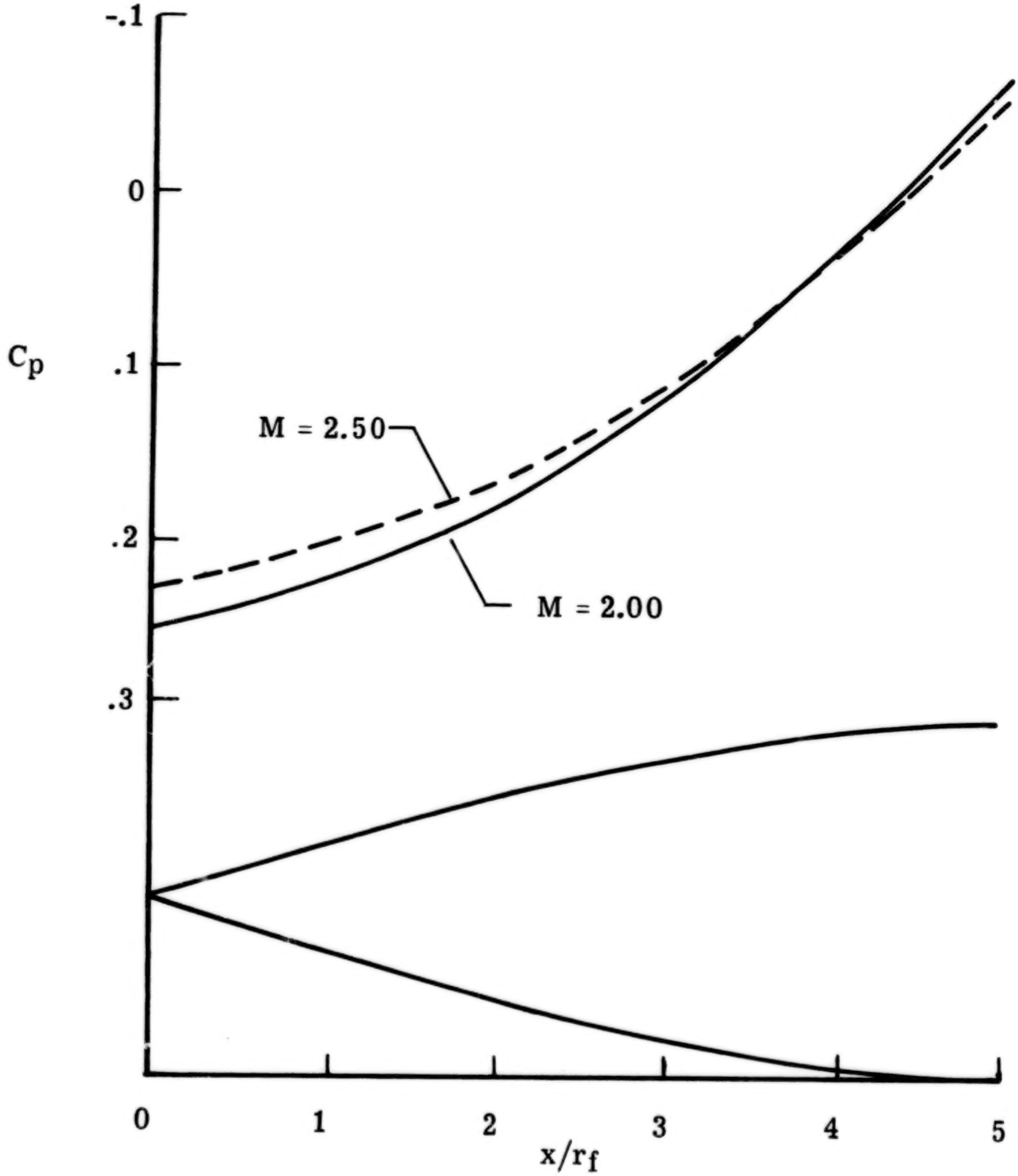
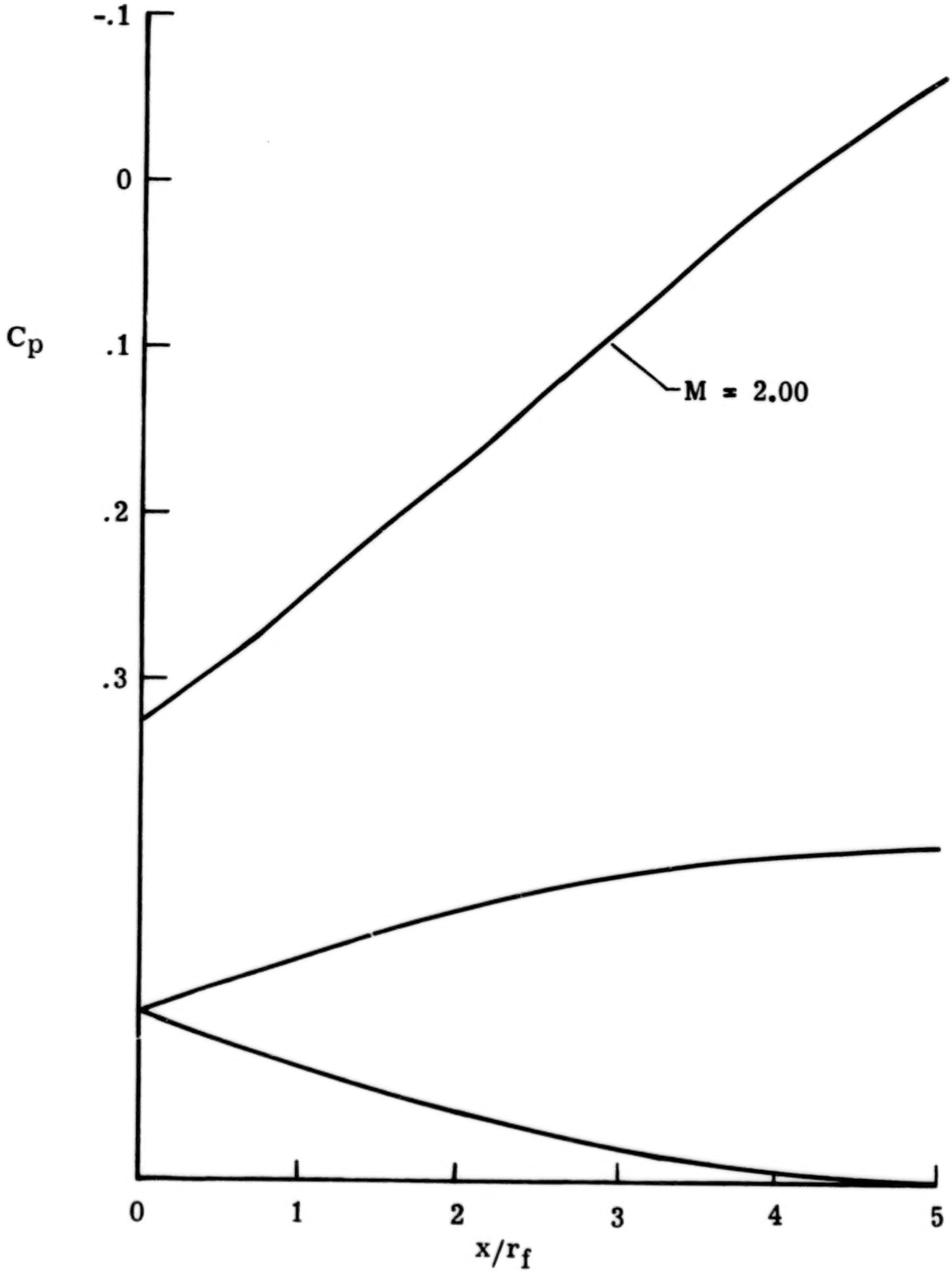


Figure 2.- Pressure distributions for forebody shapes of figure 1; M = 0.75.



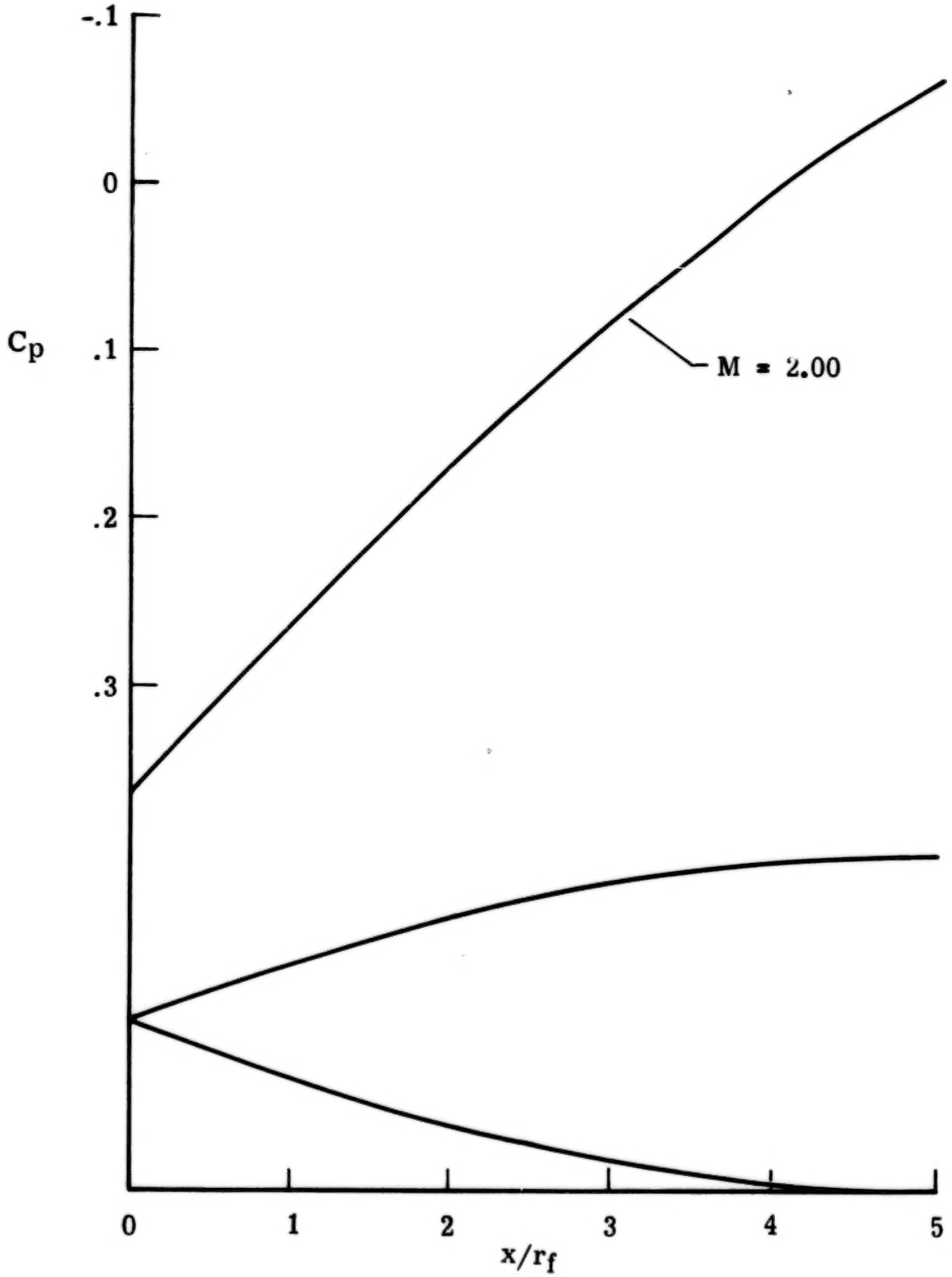
(a) k = 2.

Figure 3.- Supersonic forebody shapes and pressure distributions for different values of parameter k.



(b) k = 5.

Figure 3.- Continued.



(c) k = 11.

Figure 3.- Concluded.

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16. Abstract

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